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Tools for Developing Bay Delta Restoration Performance Metrics

Prepared for:

The Bay Institute of San Francisco

by:
Anitra Pawley, Ph.D.
Consultant to The Bay Institute
709 N Street, Davis, CA. 95616
phone: (530) 756-9892
fax: (530) 752-3350

Table of Contents

Summary

During the past twenty years "adaptive management" has been applied to a range of issues, including the rehabilitation of salmon stocks in the Columbia River Basin, water management in the Florida Everglades and the management of forest reserves. This document sets out a framework drawn from these examples, to provide a basis for the adaptive management process that the CalFed Bay Delta Program is currently involved in. We attempt to clarify the adaptive management approach as it relates to restoration and suggest specific methodologies (tools) to define the problem, choose indicators and performance metrics. Geographic Information Systems (G.I.S.), historical attribute lists, conceptual modeling and simulation modeling are tools that can inform the restoration process.

Though the identification of multiple indicators (measurable parameters used to evaluate "ecosystem health") enhances and informs the planning phase of the adaptive management process, the ultimate selection of indicators and performance metrics requires that the goals and objectives of the restoration program be clearly stated. In this vein we discuss the meaning of ecosystem management and the importance of setting goals that enable the recovery of a functioning river and delta ecosystem, by working at multiple scales of ecological complexity.

In order to select indicators and their associated "performance metrics" (target ranges or measures), it should be recognized that these efforts can not be undertaken without an adequate scientifically based planning and evaluation phase. The best indicators are those that are: 1) sensitive enough to serve as early warnings of change, 2) distributed over broad geographic areas and widely applicable, 3) less affected by or exhibit low variability to natural change, 4) easy and cost effective to measure, collect, assay, and/or calculate, 5) relevant to ecological phenomenon, 6) relevant to the type of management measure or restoration action chosen for evaluation, and 7) represented in a baseline data set or known from the historical record.

The methods for determining performance metrics are as varied as the tools used in ecological study; however, we summarize the most commonly used methods ranging from the use of professional judgement to more involved techniques such as simulation modeling and experimentation. A large scale restoration project such as that proposed by the CalFed Bay Delta Restoration Program should not rely on a single approach for establishing "performance metrics", but should incorporate a variety of approaches to ensure a significant level of redundancy in its evaluation criteria.

Introduction

The goal of ecosystem restoration and management is to restore and sustain natural ecosystem integrity ("ecosystem health") by protecting native habitat values including the biodiversity and the ecological processes that sustain this diversity (modified from Richter et al., 1996). How should this goal best be achieved? More than a century of ecological research and natural resource management has taught us that ecosystems are far more complex and difficult to manage than was previously anticipated. This complexity requires resource managers to study a wide range of ecosystem variables in an organized and analytical fashion, to distinguish these variables, and to set priorities for management strategies that both the scientific community and the public can support.

Because ecosystems are characterized by variability and at times sharp shifts in behavior, ecosystem management and restoration techniques must also be designed to account for uncertainty (Holling 1978). The recognition of this uncertainty lead C.S. Holling and co-workers at the University of British Columbia and the International Institute for Applied Systems Analysis to suggest an approach called "adaptive management". This approach is based on the recognition that almost all successful endeavors require a trial and error approach (Holling 1978). "Adaptive management is a formal, systematic, and rigorous approach to learning from the outcomes of management actions, accommodating change and improving management. It involves synthesizing existing knowledge, exploring alternative actions and making explicit forecasts about their outcomes. Management actions and monitoring programs are carefully designed to generate reliable feedback and clarify the reasons underlying outcomes. Actions and objectives are then adjusted based on this feedback and improved understanding. In addition, decisions, actions and outcomes are carefully documented and communicated to others, so that knowledge gained through experience is passed on, rather than being lost when individuals move or leave the organization." (British Columbia Forest Service 1998)

During the past twenty years "adaptive management" has been applied to a range of issues, including rehabilitation of salmon stocks in the Columbia River Basin, water management in the Florida Everglades and the management of forest reserves. Unfortunately pursuing environmental management using the "adaptive management approach" frequently leads to more questions than answers. Those attempting to plan adaptive management "experiments" are often lost in a quagmire of policy issues, disagreements of scale, and discussions over which component of the ecosystem to restore. Despite the "adaptive management" strategy's apparent clarity of purpose and procedure, both Walters (1997) has criticized the lack of success in applying this technique over the past two decades. Furthermore, in searching for ways to choose indicators and associated "performance metrics" or "targets ranges or thresholds" for program evaluation, it is difficult to find a document that summarizes these methods. Although there is no recipe for restoring aquatic ecosystems; there have been advances in our knowledge of system processes and indicator development that may help us make procedural decisions based on sound scientific approaches. An analytical adaptive management approach that has procedural clarity and incorporates scientific analysis and modeling, should help ensure a higher degree of accountability and success in restoration. We offer some clarification and elaboration of the adaptive management strategy as it can apply to ecosystem restoration planning and implementation in a large scale California watershed dominated by riverine processes. This summary attempts to

C-015087

clarify the adaptive management approach as it relates to restoration, suggest solutions to inherent impediments in the planning process by providing specific methodologies (tools) to define the problem, choose indicators and performance metrics. Before moving to the proposed framework, it is important to examine some of the issues that impair progress in designing ecosystem management strategies.

The Significance and Meaning of Ecosystem Approaches

With each riparian and riverine "restoration experiment", restoration practitioners have become increasingly aware of the need to perform restoration from an ecosystem perspective with a more thorough understanding of the complex connections between physical and biological processes in both space and time. Riverine ecosystems are characterized by a high degree of connectivity and geographic and temporal variability. Many past restoration efforts lacked the information needed to account for these factors: failed fish passage structures, streambank vegetation and erosion control efforts attest to this fact. Projects that were too narrow in scope, focussing on individual processes or single species frequently failed because of the lack of attention to larger scale processes that are essential to ecosystem function. (Alevizon et al. 1996) The failure of many of these projects, enhanced the realization that restoration projects must be coordinated to re-connect essential ecosystem processes and ensure "ecosystem health"(Sparks 1995). To restore these systems, restoration programs developed via adaptive management must operate on the scales necessary to account for these realities.

Ecosystem-level restoration efforts should attempt to rehabilitate a suite of structural and functional characteristics of entire habitat types (e.g., stream channel, riparian corridors, and tidal wetlands) and ensure the connection between these habitat types (Alevizon et al. 1996). Though

C-015088

there is a fair consensus that ecosystem strategies are necessary (Noss 1990), ecosystem management does not necessarily restrict itself to operating at one spatial scale. While it is important to define appropriate scales, it is usually necessary to operate at several levels of organization. "Ecosystem Management depends on research performed at all levels of organization, from investigations of the morphology, physiology and behavior of individual organisms, through studies of the structure and dynamics of populations and communities, to analysis of patterns and processes at the level of ecosystems and landscapes" (Christenson et al. 1996). Consequently, it is necessary to work across multiple organizational scales to aggregate the necessary information that is needed to support a large-scale restoration program. Experts should be chosen from many fields that focus on various spatial scales, including ecosystem, community, population and behavioral ecologists.

Restoring Ecosystem Function

Though there are few examples of completed large-scale riverine projects, we can learn significant lessons from the experience of others who participated in planning these efforts. During the Kissimmee River Restoration Project, Toth (1995) noted that the resource management interests of federal and state agencies (and even within agencies) were on the verge of becoming divisive. Though the objectives of the various entities involved were all related to the channelization of the river, they quickly expanded to include a wide array of environmental values, that were evaluated independently in a non-integrated fashion. In recognition of these multiple objectives, some project engineers suggested that optimization techniques could allow the requirements of the individual species to be molded into one plan; however, Toth (1995) noted

C-015089

that this was not necessarily a suitable goal. Species populations are rarely stable. Because there can be competition between individual species and even between life history stages of one species, it is not possible or perhaps desirable to attempt to re-create historical conditions in this manner. "Natural ecosystems, like pre-channelization Kissimmee River, have a level of organization that transcends the optimal requirements of its individual components, and no criteria specifying individual species requirements, whether alone or in combination, would reestablish the complex food webs, river and floodplain habitat heterogeneity, and physical, chemical, and biological processes and interactions that determined the biological attributes of the former system." (Toth 1995). This realization lead participating scientists and a scientific review panel at the Kissimmee River Restoration Symposium held in 1988 to recommend an ecosystem restoration perspective that emphasized reestablishing the *ecological integrity* of the Kissimmee River ecosystem. The approach was to focus on reestablishing the forces that once created and maintained the historic ecosystem prior to river channelization, the reestablishment of the natural river channel and floodplain morphology.

A review of recent literature leads us to the fact that Toth (1995) is only one of many authors that stress the importance of hydrology and geomorphology in the maintenance of riverine ecosystems. The goals of a river based ecosystem restoration program must reflect the processes that created riverine and delta ecosystems. These processes and more general ecosystem principles should be an explicit part of the objectives of the program. They include:

-- Restore or maintain the natural inter-annual variation of the hydrograph, including the magnitude, frequency, duration, and timing of the discharge (Poff et al. 1997).

-- Restore or maintain geomorphological processes to ensure the connection of a river with its floodplain, and an area for meander, overflow and depositional processes that ensure natural habitat function.

-- Restore "natural habitats" including the values that make each habitat distinct and essential to the maintenance of its resident biota. This depends on the restoration of natural hydrologic and geomorphologic processes; however, component habitat-types have more specialized attributes that distinguish them as ecologically different areas (i.e., distinctive structural attributes including water quality) (adapted from Alevizon et al. in press).

-- Restore landscape diversity and connectivity. Each ecosystem has a characteristic arrangement of habitats or habitat mosaic. Riverine ecosystems are known for their important role as migration corridors. Without the maintenance of this mosaic of habitat types and natural connectivity, many riverine landscapes will never exist as they once were.

-- Maintain and restore overall biodiversity and community structure. This is generally the primary goal of most restoration/management programs, but it is also an essential aspect of restoring habitat structure and most fundamental ecosystem processes, including primary production, nutrient cycling and exchange.

-- Encourage and restore "natural" relationships between species including predation, competition, parasitism and mutualism. These processes lead to natural trophic structure and ecosystem processes such as nutrient cycling.

The San Francisco Bay-Delta-River System

The San Francisco Bay Delta River system is an important watershed for a protocol and a series of consistent methodologies to plan, implement and analyze the outcome of aquatic restoration projects. It is currently the focus of a large-scale restoration planning effort called the CalFed Bay-Delta Ecosystem Restoration Program, part of a larger joint state-federal effort to solve longstanding conflicts over use of the estuary's waters.

"The mission of the CalFed Bay-Delta Program is to develop a long-term comprehensive plan that will restore ecosystem health and improve water management for beneficial uses of the Bay-Delta system"(CalFed ERPP Executive Summary, 1997). The program is divided into four resource areas: ecosystem quality, water quality, system integrity, and water supply reliability. The CalFed Ecosystem Restoration Program Plan (ERPP) addresses the ecosystem quality resource goal and is divided geographically into 14 ecological zones that follow the length of the Sacramento and San Joaquin Rivers along their paths to the ocean (CalFed ERPP Vol. I, 1997). The goal of this plan is to improve and increase the extent of aquatic and terrestrial habitats and improve ecological functions to support sustainable populations of valuable plant and animal species in the Bay-Delta (CalFed ERPP Executive Summary, 1997). The plan seeks to emphasize an integrated systems approach that recognizes the importance of natural forces and their role in the creation of historic habitats and the use of these forces to regenerate habitats.

A working list of four ecosystem types deemed most relevant to the CALFED program has been developed: (1) upland and (2) lowland river-floodplain systems (defined respectively as those river-floodplain areas either above or within the alluvial deposits of the Central valley floor), (3) the legal Delta, and (4) greater San Francisco Bay (including Suisun Bay). We have selected the

C-015092

legal Delta or Delta Ecoregion as an example for applying adaptive management planning tools for the San Francisco Bay-Delta Watershed. The Delta Ecoregion is a central focus of the ERPP and a place where the Sacramento and San Joaquin rivers historically formed an extensive system of wetlands, islands, riverine channels and sloughs that emptied into the San Francisco Bay estuary. The importance of restoring or at least rehabilitating the delta is without question: the delta is a conduit for runoff from over 40% of California's surface area (Kahrl 1978) and has been highly impacted by the diking and filling of wetlands, water diversions causing reductions in freshwater inflow by more than half, the introduction of exotic species, and the influx of pollutants (Meng and Moyle 1995).

Adaptive Management Framework for Restoration Programs

We elaborate on a framework which enumerates and explains the alternative methodologies that can lead to an effective restoration program in aquatic ecosystems, with emphasis on problem definition, and the choices of management measures, indicators and performance metrics. The following framework is a synthetic approach to restoration planning and implementation: an approach that emphasizes adaptive management and the restoration of natural ecosystem function. The following steps are adapted from the adaptive management process as it was first suggested by Holling (1978) and elaborated on in the British Columbia Forest Service guide entitled, "An Introductory Guide to Adaptive Management for Project Leaders and Participants"(1998):

1. problem assessment;
2. design;
3. implementation;
4. monitoring;
5. evaluation; and
6. adjustment.

The first two steps are essentially the steps that encompass the *planning phase* of the adaptive management process. The CalFed Bay Delta Ecosystem Restoration Program is currently in this critical phase. It is hoped that by elaborating on these steps (1 and 2) and the tools that can assist scientists and resource managers during the planning phase of the adaptive management process, we can offer some insights into the design of restoration projects and monitoring programs before critical and costly mistakes are made.

The planning framework we propose is a series of steps including recommendations for defining the problem via conceptual models, the selection of restoration and management strategies, the establishment of appropriate indicators and associated "performance metrics" (also called "performance criteria" or "target ranges") and predictive and empirical approaches to determine whether these strategies are appropriate. It should be noted that this is not a series of steps to be followed in exact order, but rather a series of tasks and a set of tools that provide options for choosing an appropriate path for restoration project design and subsequent evaluation. The steps of the planning framework will often require multiple iterations to proceed to an adequate restoration program plan.

1. Define the scope and scale of the problem

The first step in any ecosystem restoration project, whether large or small in scale, is to define the problem and determine the goal(s) of the restoration effort. This is best accomplished in one or more workshops where participants define the scope of the problem, synthesize existing knowledge about the system, and explore the potential outcomes of alternative restoration strategies. Explicit hypotheses on the causes of ecosystem impairment and predictions of

C-015094

ecosystem response to management actions enable the subsequent evaluation of the restoration program. "During this exploration and forecasting process, key gaps in understanding of the system (i.e., those that limit the ability to predict outcomes) are identified." (British Columbia Forest Service 1988)

Holling (1978) emphasized the utility of performing these tasks in a workshop setting and of having a "core group" meet prior to these workshops to plan and prepare outlines of conceptual models to guide the process if it falters. "The core group is a small group of people that interacts with a wider set of experts during a series of short-term intensive workshops. This circumvents the tendency that large interdisciplinary teams have of breaking the problem into so many parts that nothing seems to "get done". The objective of the workshop should be to generate a model that summarizes the restoration problem, causes, and associated hypotheses. The model need not be precise but should serve as a means to focus the efforts of the group. Model formulation forces the workshop participants to define the spatial scale, temporal scale, and range of factors (i.e., variables) to be considered when evaluating the problem. Models can take various forms from conceptual ecosystem models to numerical models where projects are more finite in scope (See Restoration Planning Tools below). The following steps are part of the model formulation process.

1.1 *Define the scope of the problem*

There is no one way to design a restoration program and each program is subject to the constraints of economics, policy and the opinions of the players involved. Nevertheless, without a clear definition of the problem, a restoration plan is inherently unfocussed and likely to fail. Defining the problem and developing clear objectives is a particularly difficult task for large-scale multifaceted projects such as CalFed's Ecosystem Restoration Program Plan (ERPP).

C-015095

1.2 *Define measurable restoration and management objectives and list potential actions*

Once the restoration problem has been defined, it is possible to determine restoration objectives and list the possible restoration and management actions that will meet these objectives. It is critical to be clear about restoration objectives at the onset of the program, so that management actions reflect these objectives. At the broadest level one must determine whether the project hopes to restore the ecosystem to historic conditions or rehabilitate the system to some other intermediate level. For example in a recent review of the initial ERPP, a scientific review panel noted the lack of clarity in the statement of project goals (CALFED Bay-Delta Program 1997e). Further work to refine these goals and specific measurable objectives based on these goals, is a prerequisite to constructing an adequate management framework. Objective setting is not purely a technical process, but requires collaboration between public policy and scientific knowledge.

The selection and evaluation of management measures is an iterative process that requires a close connection between the definition of the problem, the adoption of measurable restoration objectives, the selection of specific management measures, the selection of indicators and their associated numerical values ("performance metrics") and a reevaluation of the management measures once their impact on restoring ecosystem attributes is assessed. Management measures are actions that will have direct or indirect impact on ecosystem health. Obvious examples include restoring the natural hydrograph or some approximation of the natural hydrograph, creating setback levees, and eliminating exotic species. The iterative nature of this process will become clear once we proceed through the series of steps suggested below.

1.3 *Develop a list of environmental indicators that are closely tied to management measures*

To evaluate the success of the chosen management measures it is necessary to choose a set of consistent and measurable parameters or ecological "indicators". An ecological indicator is a measurable quantity that provides information about the property of a system and its "ecological health" (Levy et al. 1996). A large-scale restoration plan should encompass a wide range of indicators that operate on several temporal and spatial scales to ensure that "ecosystem health" is restored. See the indicator development section for a more thorough discussion of indicator development and the performance metric section for examples of how "target ranges" or "threshold values" can be determined, once indicators are chosen.

1.4 *Explore the effects of alternative management actions on indicators using models or small scale experiments and make explicit predictions about what will occur if actions are implemented*

The chosen set of indicators and the ecological responses they measure, can be more than a means to evaluate the response of certain specified actions, but also the tools to choose appropriate management actions. By utilizing graphical techniques and modeling approaches as a means of determining how management actions affect the "indicators ", we can provide guidance to the ecosystem manager before "on the ground" restoration begins. Conceptual models can provide the starting point for exploring the effects of management actions by providing a visual picture of the ecosystem links affected by stressors and hence a means to suggest the necessary management actions aimed at stressor reduction. Simulation models can be used to evaluate the results of employing management actions at specific levels by incorporating indicators as response variables and projecting the changes in these variables over time and space. If used judiciously, these models can help assess the consequences of alternative actions and hence assist the restoration project planners choose appropriate restoration strategies (See Ecosystem Restoration Tools below).

1.5 Identify uncertainties in knowledge of ecosystem responses

By exploring management alternatives and predicting probable responses via conceptual and simulation models, key gaps in understanding of the ecosystem will emerge. These key uncertainties should be expressed as alternative hypotheses of system function, in the form of written hypotheses or graphical relationships. The explicit declaration of uncertainties may lead to a series of alternate hypotheses which can serve as the basis to design adaptive management experiments and also the basis for "scenario analysis" in simulation modeling exercises.

2. *Design Restoration/Management Plan and associated Monitoring Program*

Restoration programs frequently lack the necessary focus on long term evaluation to determine if efforts are successful. The failures of past exercises in adaptive management emphasize the importance of pursuing restoration in an organized and scientifically defensible manner with adequate hypothesis testing, controls, and monitoring to evaluate outcomes. The management plan and monitoring program should be designed to provide informative and reliable feedback. Typically, this involves comparing a range of management actions through experiments that are deliberately designed as management experiments, to discriminate between alternative hypotheses, an approach termed "active adaptive management". The alternative method, referred to as "passive adaptive management", is to assume that the most plausible hypothesis is true and implement the action or set of actions that models forecast will promote the best outcome. Passive adaptive management is usually employed when there are impediments to designing "on the ground" experiments, such as high economic or ecological costs. Where past actions or natural disturbances have provided reliable information and certainty about responses to a range of conditions, passive adaptive management approaches are favored.

Although Walters (1997) has emphasized the importance of large scale experimentation, it is exceedingly difficult to perform large scale <u>controlled</u> experiments in riverine systems. The linear and dynamic nature of riverine ecosystems leads to a high degree of annual and inter-annual hydrologic and biotic variability, which is not easy to characterize and reproduce on any scale. The best method for the CalFed Bay Delta program is probably a hybrid of both active and passive adaptive management approaches. For the CalFed Bay Delta program, we can perform small-scale experiments as part of funded research programs and larger scale experiments in the

C-015098

form of demonstration projects to test many of the hypotheses that have not been adequately evaluated. For example, within the Estuarine Ecology Research Team (EET) of the Interagency Ecological Program (IEP) there is significant discussion over what drives some of the relationships noted for fish populations. For example, the location of the 2 ppt salinity gradient in the San Francisco Bay Delta has been found to be highly correlated with the abundance of many estuarine species (Jassby et al. 1995). The X-2 – estuarine species abundance relationship varies with numerous factors. Therefore while X-2 is a good candidate for a landscape level indicator of the viability of many estuarine species, it is also important for future management efforts to isolate these relationships via experimentation. Experiments can better elucidate the optimal conditions for certain species and provide guidance for a restoration process that addresses the factors that are most responsible for the viability of native fish populations.

2.1 Determine which restoration and management options are to be implemented and in what configuration

Though the selection of restoration sites may be constrained by political and social opportunities, if at all possible one should select sites where restoration is likely to reap the most benefit for overall ecosystem "health" and have a high probability of success. Though still young, the science of conservation biology has developed to the extent that it can provide significant guidance on the choice of restoration sites. In addition, Geographic Information Systems (G.I.S.) and simulation models incorporating regional data can assist the CalFed Bay Delta Planning Team determine suitable areas for restoration and select from a variety of management measures.

As noted above, the restoration project(s) should be performed as experiments. "Ideally, a well-designed management experiment should include controls; replication of treatments in space and time; allocation of treatments to control for bias and environmental gradients, and to ensure statistical independence; and evaluation of confidence levels and power.

C-015099

Researchers and statisticians can provide valuable assistance in designing management experiments." (British Columbia Forest Service 1988)

2.2 Design a monitoring protocol that includes the indicators and performance metrics chosen above as a means to evaluate the success of the restoration program.

2.3 Specify the observation thresholds or measured trends that would trigger a change in management

2.4 Plan data management and analysis

2.5 Use the results of the monitoring effort to evaluate the success of restoration efforts, adjust management actions and further refine the ecological model(s) if they are need for additional restoration scenarios

Ecosystem Restoration Planning Tools:

Natural Ecosystem Attributes List

Lists of key ecosystem attributes can serve as a convenient and necessary "check list" of environmental factors that might be addressed in an ecological restoration/rehabilitation context. To be useful, the attribute list should summarize over an appropriate hierarchy of spatial scales, the natural ecological characteristics that define and distinguish the specific ecosystem, including key relationships. To determine key attributes one should review, analyze, and summarize available information on (1) the historical state of these systems, (2) relatively "pristine" remnant sites within the watershed, or (3) similar types of systems at other locations. The attributes list should represent the best current evaluation of the condition of the system in its natural or pristine state, which is not necessarily identical to the "target state" of a restoration program (Alevizon et al.1997). To be manageable, large ecosystems require attribute lists at a variety of spatial scales, preferably in a nested hierarchy. The division of these attributes into consistent categories makes it possible to compare riverine systems, within river subunits, and enhances our ability to move between different hierarchical scales in an organized fashion. (*Appendix 1 includes an example of an attribute list for the Delta Eco-region developed by the Indicators Workgroup.)*

Conceptual model of ecosystem function

To identify key properties of the ecosystem that have been adversely impacted by human induced stress and the degree to which prospective restoration sites diverge from a "healthy" or "natural" condition, it is essential to develop a basic understanding of the natural structure, function and organization of the systems to be restored. A conceptual ecosystem model facilitates the identification of key ecosystem components and can help describe ecosystem linkages and the functional relationships between management actions and indicators. Conceptual models in various forms (e.g., box-and-arrow diagrams, matrices, graphs, equations) can be produced with the level of detail dependent on available information and on the specific goals of the restoration effort. As noted above, large-scale systems may require a hierarchical approach to ecosystem description and model development. The targeted restoration area may be too large to model as one ecosystem, but instead should be broken into smaller sub-units (i.e., eco-zones or habitat types) for the modeling effort. For example, if a restoration effort is aimed at the restoration of habitats, a model might group trophic levels as they interact with specific habitat values. A more explicit species interaction model would be required if the goal is to restore specific endangered or threatened species. These models can be designed in a nested manner to allow for cross calibration and the sharing of model parameters where it is meaningful.

In addition to understanding how various ecological components interact, conceptual models are useful for determining the vital links disrupted by specific stressors. By describing these impacts in an explicit fashion, we can identify the management measures necessary to eliminate or reduce these impacts and suggest the appropriate "indicators" that will record our progress in achieving our goals. As we will discuss below, the conceptual models can serve as a starting point for mathematical simulation models depending on the amount of data available and the assumptions the modeler is willing to assume. *(Appendix 2 includes an example of a preliminary conceptual model for the Bay-Delta Eco-region developed by the Indicators Workgroup.)*

C-015102

Simulation Models

Walters (1997) noted the importance of modeling as a tool in planning large scale riparian and coastal management projects: "...today we generally use the term (*adaptive management*) to refer to a structured process of "learning by doing" that involves much more than simply better ecological monitoring and response to unexpected management impacts. In particular, it has been repeatedly argued (Holling 1978, Walters 1986) that adaptive management should begin with a concerted effort to integrate existing interdisciplinary experience and scientific information into dynamic models that attempt to make predictions about the impacts of alternative policies. This modeling step is intended to serve three functions: (1) problem clarification and enhanced communication among scientists, managers, and other stakeholders; (2) policy screening to eliminate options that are most likely incapable of doing much good, because of inadequate scale or type of impact; and (3) identification of key knowledge gaps that make model predictions suspect."

Ecosystem modeling efforts aimed at riverine systems are still in their infancy, however, there are some general hydrologic and trophic interaction models that can be adapted to specific riverine systems and a plethora of more generalized population models that offer guidelines for modeling population responses (Lande and Barrowclough 1987). Because modeling ecosystem properties is less permanent and generally far less expensive than structural changes to the ecosystem, an approach that incorporates mathematical modeling can help avoid costly mistakes and ensure that ecosystem restoration is an economically and ecologically viable process. We can use ecosystem/population models to compare the relative importance of various indicators and "performance metrics" and as a means of predicting whether these metrics are attainable.

Modelers term this approach "scenario analysis" (Starfield 1997), an approach used in the context of management to run simulations designed to answer a number of "what if" questions.

The predictive ability of ecosystem modeling approaches depends on the degree of information known about the ecosystem: the amount of available data on key variables and the stochasticity inherent in the system modeled. Conceptual models provide the basis for the mathematical modeling effort; however, for a mathematical modeling approach to be successful, it is important to have a focused research design. A "modeler" must form a specific research question or hypothesis and choose variables that reflect this goal. Like diagrammatic conceptual models, the numerical model varies in its specificity, depending on the research question being addressed. One may attempt to describe how entire landscapes, ecosystems, or communities respond to environmental or human induced change or how specific species respond. Models can be built as sub-units or sub-models to create a framework that is adaptable to additional modeling efforts. The following steps provide general guidelines for a mathematical modeling effort.

a) Choose the problem to be addressed and determine the appropriate research objectives and hypotheses

b) Choose the appropriate geographic and temporal scale of interest (If undertaking a large scale project, it may be appropriate to divide the area into smaller ecological zones or habitats for the analysis). Generally, the more specific the hypothesis and targeted area, the better the predictive value of the model.

c) Determine state variables from available information including published scientific studies, agency reports, and documented data sets. Examples of state variables include hydrologic phenomena (i.e., discharge, surface area, grouped trophic levels, or particular populations). *State variables may equal indicators for the estimation of "performance metrics".*

d) Determine how these variables interact and estimate parameter values that control process rates such as fecundity, birth rate, growth rate, etc.

C-015104

e) Add demographic and environmental stochasticity to the model where necessary

f) Run simulations and evaluate whether results are realistic. (For example, are model generated hydrographs realistic? Are population abundances appropriate?) In most cases it is best to run the model under different conditions to determine the model's performance. If necessary, adjust variables and parameters to reflect actual conditions.

g) Perform a sensitivity analysis to determine which aspects of the model (variable or rate determining steps) are most sensitive to changes in management measures

An Example Simulation Model: The Hydraulic-Food Chain Model:

The following example, which is being developed by The Bay Institute, illustrates how a hydrographic and food web model can be linked to generate predictions in the Delta Ecoregion. In this modeling effort, we will compare the outcome of specific management scenarios in a riverine floodplain, select indicators (as variables), and evaluate certain "target ranges" for these variables.

It is now recognized that shallow water areas and the dynamic processes that created them are attributes that should be restored, particularly to rehabilitate this extremely impacted ecosystem and its native fish inhabitants (CalFed ERPP Vol. I 1997). However, despite this general agreement, there is still debate over the quantity and location of habitat to be restored. The CalFed ERPP proposes to restore approximately 10% of the delta floodplain habitat but it is unclear how this percentage was reached or specifically how this goal is to be obtained. It is also uncertain what freshwater flows are necessary to ensure inundation of restored wetland areas during key spawning and rearing seasons and how fish entrainment will modify population survival rates over time. In general, we are lacking even a semi-quantitative framework to adequately evaluate the probable population responses of alternative management approaches affecting floodplain habitat.

C-015105

We are pursuing a modeling approach that combines a hydrologic-geomorphic model with ecosystem and population modeling techniques to model effects of management strategies such as structural modifications of a floodplain and varying levels of inflow. There are few examples of riverine ecosystem modeling and even fewer that combine the strengths of physical process models, ecosystem models, and population viability analysis techniques. Malanson (1993) noted the importance of combining three types of systems models, hydrological, geomorphological, and ecological models to develop a synthetic approach to modeling landscape dynamics. Though most scientists stress the importance of focusing on the restoration of whole ecosystems (i.e., watersheds) instead of single species (Noss 1990), only fairly recently have scientists begun to develop usable models for these systems. Even spatially explicit hydrologic models are rarely linked to models describing geomorpological or ecological processes. Frequently hydrologic models do not incorporate over-bank flooding and sedimentation, so they need modification to provide ecological reality (Malanson 1993).

The hydraulic food chain modeling approach developed by Power et al. (1995a) provides a means to explore the linkages between physical hydrodynamic and geomorphic processes and riverine food webs. Factors that vary with river discharge such as depth, width, and velocity affect the performance of organisms and therefore of trophic groups. Power et al. (1995b) used a simple hydrologic model based on the Manning equation to investigate the effects of several floodplain widths on a detrital and vegetation based food web composed of seven members and five levels. In their model, two factors were linked with hydraulic parameters: vegetation increased with discharge to some optimal level and then decreased, and bird predation declined with increasing depth. Detrital energy inputs varied seasonally with pulses of detritus available upon flooding and constant amounts thereafter. These energy inputs were incorporated into invertebrate biomass by assuming constant attack rates. Invertebrates were consumed by small and large fish and for large fish the model was designed to account for the effects of vegetation density on attack rates (refuge effects).

This hydraulic food chain modeling approach will be modified to allow us to test the effect of different restoration and management scenarios on indicators and their associated "performance metrics" in a specific site within the Delta Eco-region. Though the indicators can be surrogate measures of the variables in the model, a preferred situation is to maintain direct linkages between the indicators and the model so that the results of the modeling effort are easily translated into management strategies. Once the model is created, we can run simulations using differing starting conditions and levels of stochastic variation by incorporating Monte Carlo techniques (Getz, pers. comm.) to determine the effects of the management options on our "model floodplain ecosystem". The results of these simulations will assist us in recommending the best approaches for restoration.

Geographic Information System Techniques (Spatial Analysis)

Geographic Information Systems are rapidly becoming a common tool for watershed planning and management. The Gap Analysis project of the U.S. Fish and Wildlife Service, a spatial assessment which is used to determine priorities for protection, demonstrated that a visually compelling map backed by data can do more to stimulate proactive environmental action that any number of words (Noss 1994) By combining vegetation maps produced from remote sensing imagery with wildlife habitat association models and information on "protected areas" (park boundaries, etc.), the Gap Analysis project identifies gaps in species protection features (Scott et al. 1993). Though the Gap Analysis project is based primarily on terrestrial features in the form of grid or polygon coverages, digital line graph or vector files can work well to represent aquatic. The EPA River Reach File (RF3) has significant potential as a format that can be used to tag specific river reaches based on specific restoration features (Pawley et al. in press).

In the CalFed Bay Delta region, there are numerous agencies and watershed groups developing separate G.I.S. databases; however, the data from these efforts need to be coordinated and made more accessible if these separate G.I.S. databases are to be made useful for regional restoration planning. Website database technology is improving rapidly and this has significant potential for increasing the ability to access data from traditional databases and G.I.S. databases over the Internet. Despite these improvements, there are impediments to data transfer and acquisition that a large-scale federal and state supported G.I.S. project could help circumvent. Agencies and other entities commonly have significant problems transferring G.I.S. coverages between themselves due to incompatible database technologies. In California, the TEALE Data Center (URL = http://www.gislab.teale.ca.gov), has traditionally been the primary location to acquire standardized statewide datasets, but the costs associated with obtaining a site license to use the coverages can be staggering for many watershed groups and individual researchers.

A Geographic Information System developed for the CalFed Bay Delta Plan Region on various spatial scales could house significant amounts of resource information and serve as a means to coordinate the efforts of local watershed groups which may be starting local systems or needing a G.I.S. data repository. A regional G.I.S. could provide the necessary background to make decisions on restoration site location, size, and connectivity. For example, a G.I.S. database could be developed to help determine the number and spatial extent of floodplain restoration sites needed to support fish production and/or spawning habitat of certain rare fish species. This database could house information (coverages) on: the spatial extent of historical natural levees and wetland habitat distribution (provided old maps and paleontological data are available), information on suitable floodplain opportunities (i.e., areas that can be made available for flooding using information on city and county developed areas and elevational gradients), the present distribution of levees, and information on present distribution of species (or migration patterns) that could colonize the proposed floodplain habitat. This information in the form of G.I.S. coverages could then be superimposed and a set of decision rules created in order to choose the sites most likely to provide suitable floodplain restoration opportunities. Information from the G.I.S. for a specific area or for the entire region (i.e., acres of flooded wetland habitat) could subsequently be entered into simulation models to hypothesize how much benefit would be gained by such projects (i.e., improvement in fish populations).

Indicator Development

To evaluate the success of the management measures chosen during the adaptive management process it is necessary to choose a set of consistent and measurable parameters or ecological "indicators". An ecological indicator is a measurable quantity that provides information about the property of a system and its "ecological health" (Levy et al. 1996). Ecological indicators are needed because of practical constraints on the costs of monitoring. They can serve to reduce the number of variables that need to be monitored and if chosen carefully can provide an average of spatial and temporal environmental conditions. Indicators for restoration projects are essentially tests of ecosystem recovery; however, recovery is dynamic and it is inherently difficult to define recovery in terms of a single parameter (Cairns and Smith 1994). Because multiple lines of evidence must be evaluated to deem a project successful, indicators should encompass a wide array of essential ecosystem attributes and be developed for multiple spatial and temporal scales (Noss 1990). The selection of indicators must be based on their compatibility with the decision making process, reliability in reflecting the objectives of the proposed project and statistical relevance.

Due to the complexities of ecosystems, choosing the appropriate indicator is by no means an easy task. The concept of an indicator species at first glance appears simple, but it is takes significant effort to convert this concept into practice. In many cases, years of research have gone into indicator development (Spellerberg 1991). Because of the constraints of monitoring, it is necessary to extrapolate results to broader areas and at times longer time frames than can be reliably sampled (Kratz et al. 1994). Consequently one must understand the spatial and temporal variability associated with the system, and the degree to which spatial subunits of the broader ecosystem vary together in time (termed temporal coherence by Magnuson et al. 1990). To the degree possible, indicators or parameters should be chosen which are most sensitive to stress and are least sensitive to natural ecosystem variability. In summary, it is best to select indicators that are:

1) sensitive enough to serve as an early warnings of change,
2) distributed over broad geographic areas and widely applicable,
3) less affected or exhibit low variability to natural change,
4) easy and cost effective to measure, collect, assay, and/or calculate,
5) relevant to ecological phenomenon,
6) relevant to the type of management measure or restoration action chosen for evaluation, and
7) represented in a baseline data set or known from the historical record

(list modified from Kratz et al. 1994; Noss 1990).

Indicators may be very specific such as those that track the population abundance of key species; or they may record the response of multiple stressors and generally provide a picture of an average response to ecosystem disturbance or improvement. Though there is a long tradition of using indicator species to monitor or assess environmental conditions, Landres et al. (1988) and Noss (1990) emphasize the importance of using indicators as part of a comprehensive strategy of risk analysis that focuses on key habitats and processes as well as species. Examples of indicators include both structural attributes such as the amount of shallow water habitat and functional ecosystem attributes such as intact hydrologic and trophic dynamic processes that ensure fish health and survival.

To serve as a preliminary foundation for the selection of ecosystem indicators for the CalFed Bay Delta Ecosystem Restoration Program, we refer the reader to several publications including those by Levy et al. 1996, Keddy et al. 1993, Keddy and Drummond 1996, and Landres 1992. Once appropriate indicators are chosen, it is possible to define the target ranges or "performance metric" associated with each indicators. (A list of indicators most suitable for the Delta Eco-region will be included in future drafts.)

Defining Performance Metrics

Probably one of the biggest challenges to developing a restoration program is determining how to evaluate the success of the restoration effort. The process for selecting "performance criteria" or "performance metrics" is not well established. Though there are no defined thresholds for riverine systems and the ultimate judge of success lies with society, science can provide approaches and insights to deal with this issue (Paulsen and Linthurst 1994). A "performance metric" under our terminology is the value or range of values associated with an indicator that allows a determination of whether an ecosystem or population is "healthy" – in other words whether restoration objectives are being achieved and whether a restoration project is successful. Although there are guidelines for establishing indicators; the associated performance metrics for these indicators are less easily chosen. A response to restoration generally lies on a continuum from good to poor ecosystem health, so an "endpoint" or "target threshold" is difficult to define. These endpoints should be selected on the basis of the best available scientific knowledge (See A, B below); however, even with scientific information there is generally a significant level of subjectivity involved in determining target levels for each indicator. The decisions regarding endpoints are often based on establishing a desired reference condition and there are various approaches to determine what "performance metrics" match these conditions. A large scale restoration project such as that proposed by the CalFed Bay Delta Restoration Program should not rely on a single approach for establishing "performance metrics", but should incorporate a variety of approaches to ensure a significant level of redundancy in its evaluation criteria. We offer some examples of these methods below:

A. <u>Using established standards</u>

There are numerous possibilities for adopting established standards based on previous research which are codified by policy or legislation, particularly for water quality criteria (i.e., physical and chemical standards – see EPA guidance documents) (Keddy 1996). Though there are defined standards for some ecosystem attributes, the choice of management measures for a particular context should be related to regional data sources and information needs.

B. <u>Opinions of Regional Experts (professional judgement)</u>

The CalFed Bay Delta Ecosystem has a rich tradition of ecological research and hence regionally based researchers that are familiar with the ecological underpinnings of the system. A questionnaire can provide a means to enlist the help of these experts to establish a preferred list of indicators and associated performance metrics. The success of this technique depends to a large extent on the design of the questionnaire and the panel of experts chosen to answer the questionnaire. An example of this method is the Delphi Technique developed in the 1960's by Helmer of the Rand Corporation as a technique in decision analysis (Linstone and Turoff 1975, Sackman 1975). Questionnaires can be circulated by mail to a panel of experts who do not know the identity of other members of the panel. The replies are analyzed and then redistributed to the panel members with information stating the median and interquartile ranges of replies. Panel members are asked to reconsider their answers and those falling outside the interquartile range are asked to state their reasons. The second round is reanalyzed and again recirculated with the extreme replies to the panel members who are then asked to reconsider their replies.

C. Using Historical Data

If adequate historical data are available and the goal is to restore the ecosystem to historical conditions, this is probably the best method for establishing "performance metrics." Researchers at the Bay Institute have recently completed an in-depth publication describing the historical Bay Delta ecosystem, entitled "From the Sierra to the Sea: The Ecological History of the San Francisco Bay Delta River System" (Alevizon and Vorster 1998). Historical data are critical for assessing trends in riparian system health because they can provide information on environmental conditions prior to anthropogenic disturbances and the nature and magnitude of natural variability. There are many constraints on the use of historical data. Because of significant land conversion during the last 150 years and the relatively recent nature of ecological study, it is extremely rare to have enough historical data available to establish reliable endpoints.

In addition, historical data gathering methods may differ from those employed during modern times and therefore may not be directly comparable. Furthermore, it is rare to have sufficiently long time courses to establish a "picture" of natural variability. Nevertheless, gathering historical data is an extremely valuable exercise. Though it may be difficult to use the data as the only means of establishing "endpoints", the examination of historical records and even relatively recent records of change will point the researcher to the variables (indicators) that have most changed and are possible causes of ecosystem endangerment. Paleoecological (paleolimnological) studies add to our ability to reconstruct historical records.

Paleolimnological reconstructions: Paleolimnology is the science devoted to analyzing the archives contained in the sediment record (Frey 1969). Sediment cores suitable for paleolimnological analyses are usually obtained in quiescent depositional basins where fine grained sediments accumulate over time (Charles et al. 1994); and these areas are not common in stream and fast moving rivers where erosion, scouring, slumping and turbid flow are common. However, in estuaries and low gradient streams and rivers this technique shows promise. A single sediment core can provide information on levels of biota (i.e., diatoms, zooplankton) and environmental processes such as salinity, and pH can be inferred through observations of changes in biota such as diatoms (Charles et al. 1994). Paleolimnological studies have provided insight into long-term climate trends and natural variability and their causes. Fritz (1990) developed diatom based transfer functions to infer salinity changes in lakes in the northern Great Plains. Changes in water temperatures have been inferred from chironomid assemblages (Walker et al. 1991) and diatom assemblages (Snoeijs 1990). Chaoborus remains have been used as indicators of past fisheries status (Uutala 1990).

D. Using Reference Sites:

Healthy versus pristine sites: Comparisons of sites that are considered healthy (undisturbed) versus sites that are disturbed can be used to develop appropriate targets. This involves the selection of regional ecosystems that represent "pristine" conditions and the development of a suite of quantitative measurements that are used to compare the "healthy site" to the restored site. For example, a team of experienced ecologists could visit a number of critical sites, including "close to pristine sites" and "degraded sites". This team should consider what parameters to measure (independent variables, multidimensional objective assessment) and how the health of the ecosystem would be evaluated using one to several variables (dependent variables, low dimensional subjective assessment). It is best if the "independent variables" are equivalent to indicators that can be manipulated through management. Note that each ecologist should score the ecosystem independently of the others to provide extra data points and to reflect the uncertainty in subjective evaluations. A correlation study between the objective and subject variables should then be done, possibly including principle components analysis, key factor analysis, or general linear model analysis. If enough sites are available and the process captures significant differences between pristine and degraded sites, the method can be applied to sites requiring remedial action, by inferring which underlying independent variables should be manipulated using management.

Scott and Hall (1997) used this technique to develop biological indicators and metrics for the assessment of stream degradation in Maryland. Fish assemblages, stream physical habitat, and water quality were assessed concurrently at 69 sites for four years 1989-1993. Through the use of habitat and water quality information, sites were divided into two groups: those representing least-impacted streams (N = 16) and most-impacted streams (N = 22). He found

C-015115

differences in fish assemblages between the two groups: the degraded streams were less diverse and were dominated by a few tolerant taxa, whereas higher-quality sites were characterized by a more balanced assemblage structure and trophic composition. The metrics that exhibited the greatest discrimination between the groups included the number of intolerant species present, the number of shiner species, the proportion of silt-intolerant spawners in the assemblage, the proportion of tolerant fishes, and the proportion of insectivorous cyprinids.

Before and after disturbance: Site analysis before and after natural disturbances can provide the necessary setting to determine specific indicators. For example, in the tributaries of the Chesapeake Bay, the decline of submersed aquatic vegetation (SAV) has been associated with increasing anthropogenic inputs, and its reestablishment remains a major goal of a multi-state "Bay Cleanup" effort (Stevenson et al. 1993). An improvement in water quality during 1985 to 1988 provided a natural experiment in which SAV was able to persist upstream where it had not been found for almost a decade. The determination of the water quality parameters associated with successful transplants and natural regrowth over a three-year period in a major tributary, enabled Stevenson et al. to suggest target nutrient concentrations (performance metrics) where SAV regrowth was desired. In the Bay Delta ecosystem, comparisons of extreme wet years and dry years and the associated viability of particular fish species could provide insights for the refinement of performance metrics for the preferred "hydrograph".

E. Reconstructing a Niche: Using knowledge of species life history characteristics to set levels of habitat variables

Here we suggest the development of a database that houses information on the variables that characterize a species' "niche" (species life history characteristics). For rare (threatened or

C-015116

endangered species), we must establish the environmental constraints that would dictate the presence or absence of each species. If enough information is known for a wide variety "indicator species", we could establish the necessary range (performance metric) of each variable (indicator) to strive for. In other words, by applying certain mathematical relationships to this data, we could determine how these variables intersect.

Like historical data, data of sufficient quantity and quality on each target species is not likely to be available; however, this information should be acquired as restoration proceeds, particularly if species protection is a focus of the restoration effort. There is significant information on rare and endangered species in the Delta eco-region, especially on fish populations (Delta smelt, Splittail, etc.). This data needs to be better organized and made accessible to identify gaps in our knowledge of important life history strategies. An Internet site that accesses an in-depth relational "species database" would benefit the research objectives of the CalFed Bay Delta Restoration Program. This form of indicator and associated performance metric selection should be used in conjunction with other ecosystem level indicators, for the analysis of habitat structural or functional characteristics based on a few target species is unlikely to encapsulate the ecosystem properties needed to ensure "ecosystem health". For example, we envision a system that could be queried for a specific parameter (i.e., salinity), with the response being data output and possibly graphics illustrating species ranges associated with that parameter.

F. <u>Ecosystem simulation models:</u>

As described in the previous example, the hydrodynamic-food chain model, ecosystem and population models can be used to select "performance metrics". One can compare different management strategies by setting variables (indicators) at different levels (target ranges) and evaluating outcomes. Modelers term this approach "scenario analysis" (Starfield 1997), an approach used in the context of management to run simulations designed to answer a number of "what if" questions.

G. Experimental Techniques

From a methodological point of view, ecological investigation into natural communities is a complex area of research. The ecologist encounters difficulties that present themselves all at the same moment: a wide variability in the variables studied, complex interactions between the explanatory and response variables and uncertainties about the causes of observed correlations (Jongman et al. 1995). Non-experimental research of existing populations rarely yields causal explanations. Experiments can assist the restoration ecologist to narrow the potential causes and define indicators and target ranges. As noted above, it is inherently difficult to perform region wide experiments in riverine systems with adequate controls; however, medium and small-scale experiments can be designed to define indicators and target responses. Small bounded ecosystems can serve as replicates in the application of this analysis. A recent example performed in small lakes helps illustrate the use of experiment techniques to determine restoration target ranges. Harig and Bain (1998) established a set of hypotheses regarding the probable responses of lakes to the introduction of non-native fish species. They then tested the responses of 12 small, isolated Adirondack lakes via collections of fish, benthic invertebrates, zooplankton, and phytoplankton over a 3-yr period. Harig and Bain identified six indicators including dominance of native fish, relative abundance of *Daphnia*, dominant phytoplankton taxa, number of zooplankton species, dominance of large-bodied zooplankton, and zooplankton biomass. They noted that "Adirondack wilderness lakes with high biological integrity were characterized by native fish communities, by zooplankton communities with relatively greater species richness, biomass, and larger species, particularly *Daphnia* and other cladocerans, and by phytoplankton communities with few dinoflagellates."

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APPENDIX 1

DEVELOPMENT OF KEY ECOLOGICAL ATTRIBUTES FOR THE SAN FRANCISCO BAY-DELTA WATERSHED

Attribute List Subgroup Contributors (alphabetical order):
Bill Alevizon, Serge Birk, Pat Coulston, Doug Morrison, Anitra Pawley)

I. Rationale

Planning efforts directed towards restoration and protection of complex ecosystems requires a basic understanding of the natural structure, function and organization of the systems to be restored. Such understanding enables managers to assess, during planning phases of a program, the degree to which prospective restoration sites diverge from a "healthy" or "natural" condition, as well as to evaluate, after actions have been undertaken, project progress and effectiveness. In a management context, perhaps the most practical means of summarizing the most relevant existing information on ecosystems is to develop, over an appropriate hierarchy of spatial and ecological scales, a list of key system attributes - those fundamental natural ecological characteristics that together define and distinguish these systems, their status, and/or their interrelationships. Such lists of attributes may serve as a convenient and necessary "check list" of environmental factors that might be addressed in an ecological restoration/rehabilitation context. At sites for which comprehensive restoration is the goal, a full suite of applicable attributes would presumably be addressed. More commonly, at sites where partial restoration (rehabilitation) is the goal, actions and efforts would be focused upon an appropriate subset of attributes.

Some individual system attributes - such as water temperature - may be evaluated directly. Others, such as "habitat continuity", are more nebulous, and must be evaluated by developing appropriate "indicators" - measurable parameters that provide a means to objectively (preferably quantifiably) evaluate individual attributes that in themselves are not readily measured. The term indicators is also used in a broader context to refer to a *subset* of system attributes (or their measurable parameters) that are derived and used *as a group* to provide a convenient way to evaluate *overall* system status. Thus, the term "indicator" is commonly used in two somewhat different ecosystem management/restoration contexts, representing two differing scales of resolution: that of *individual* attributes, or alternately, that of *groups* of attributes. In either case, "indicators" are simply a convenient way of measuring or evaluating that which is of primary concern - system attributes. An additional, and most useful tool in understanding and describing fundamental characteristics of complex systems is the use of conceptual models that integrate and diagrammatically represent the three basic *kinds* of system components: elements (attributes), their states, and the relationships that affect attribute states.

This document develops a <u>provisional list of natural ecological attributes</u> of the ecosystems of this watershed for use in the contexts summarized above.

II. Methods

Attributes for each of the watershed's ecosystem-types were generated by reviewing, analyzing, and summarizing available information on (1) the historical state of these systems, (2) "pristine" remnant sites within this watershed, and (3) similar types of systems at other locations. They represent our best current evaluation of the condition of the system in its natural or pristine state, which may differ from a desired (or attainable) "target state" of a restoration program. "Stressors" attached to the attribute groupings represent those anthropogenic factors believed most influential in altering attribute states over the last few centuries. The attributes presented are most applicable to the broader, ecosystem level of restoration/rehabilitation planning. They represent common, fundamental ecological features of these types of systems. It is emphasized that application of these attributes (and their indicators) at particular sites will require refinement by experts familiar with the unique properties and environmental conditions found at those sites, as well as the specific goals and objectives of the particular restoration project.

For practical reasons, ecosystem attributes were organized into five broad categories, each of which reflects essential aspects of ecosystem structure/function:

> **A. GENERAL HYDROLOGIC ATTRIBUTES** - *Rationale: The integrity of natural hydrologic attributes is essential for the protection and/or restoration of native habitats and biological communities, and the maintenance of natural ecological processes (including sediment and nutrient dynamics, trophic dynamics, and salinity patterns). In rivers and streams for example, minimal flow levels are necessary to assure viability of all life stages of all native aquatic organisms, and to maintain adequate groundwater levels in support of riparian vegetation; sufficient seasonal shifts in stream level are essential to flushing, groundwater and other river-riparian exchange processes; seasonal velocity ranges and timing must be compatible with viability of all life stages of aquatic organisms, and the maintenance of sediment delivery/deposition processes, periodic flooding is necessary to maintain diversity and succession within riparian zone, and for the exchange of materials between riverine and riparian habitats.*
>
> **B. GENERAL GEOMORPHIC ATTRIBUTES** - *Rationale: The integrity of natural geomorphic attributes is essential for the protection and/or restoration of native habitats and biological communities, and the maintenance of natural ecological processes. For example, altered local topography may cause habitat fragmentation; physical barriers may prevent or inhibit natural water, sediment and or animal movement, and/or prevent reestablishment of riparian zone even if hydrologic restoration is successful; in-stream structure, sinuosity of channel, and cross-sectional profile interact with flow to determine sediment deposition*

and distribution and therefore substrate composition, a key determinant in the structuring of aquatic communities in shallow streams.

C. NATURAL HABITATS: TYPES/ATTRIBUTES - *Rationale: Within the larger framework of ecosystem hydrology and geomorphology, component habitat-type have more specialized attributes* ***(within-habitat)*** *that distinguish them as ecologically different (but highly interactive) types of areas. In a larger context, the ecosystem as a whole has attributes* ***(among-habitat)*** *related to such things as spatial distribution and arrangement of component habitat-types, and water quality. For example, the disconnection of nearby habitats (through construction of barriers or alteration of natural topography) may prevent full community development and/or restrict the distribution and viability of some populations. Both within and among habitat attributes are essential to the support of native biological communities and natural ecological processes in these ecosystems.*

D. NATIVE BIOLOGICAL COMMUNITY ATTRIBUTES - *Rationale: Restoration of natural community attributes is an essential aspect of restoring and protecting ecosystem integrity. The five defined ecosystem-types of the watershed each harbor distinctive biological communities, distributed within and among their component habitat-types. The maintenance of overall biodiversity and fundamental aspects of community structure are not only the primary goal of most restoration/management programs, but are also in themselves essential to habitat structure and many fundamental ecosystem processes, including primary production, nutrient cycling and exchange.*

E. COMMUNITY ENERGETICS/NUTRIENT CYCLING ATTRIBUTES - *Rationale: The acquisition, cycling and fate of energy and nutrients are critical aspects of ecosystem function, and essential to the support of native biological communities. Ecosystem attributes related to energy/nutrient movement are a combination of both abiological (e.g., water movement and circulation) and biological (trophic dynamics) factors.*

Attribute lists in each of these five categories were developed separately for each of four ecosystem-types deemed most relevant to the CALFED program: (1) upland and (2) lowland river-floodplain systems (defined respectively as those river-floodplain areas either above or within the alluvial deposits of the Central valley floor), (3) the legal Delta, and (4) greater San Francisco Bay (including Suisun Bay).

THE DELTA ATTRIBUTE LIST

Where the Sacramento and San Joaquin Rivers meet, their branching channels historically traversed an extensive complex of intertidal wetlands - the Delta - that merged into the larger embayments of greater San Francisco Bay. Today's legal Delta also encompasses the lower portions of the Sacramento and San Joaquin river- floodplain systems as well as some lesser tributaries (Mokelume, Calveras). This area, described below, extends between the upper extent of the tidewater (near the city of Sacramento on the Sacramento River and Mossdale on the San Joaquin River) and Chipps Island to the west.

A. General Hydrologic Attributes

1. **Water levels variable daily and seasonally**, determined generally by interactions of freshwater inflow and tides, and locally by the interactions of these factors with topography. Typically high during winter/spring and low during summer/fall. During flood events, most of the delta could be covered by 10-15 feet of water. Seasonal inundation of wetland vegetation of sufficient extent and duration to provide spawning, rearing and refuge habitat for native fish species (e.g., Delta smelt, splittail)

2. **Complex water circulation/movement patterns** determined by interactions of "natural" patterns of river discharge, tides and local topography. Net movement of water generally "downstream" (towards Bay), temporarily and regularly interrupted by incoming tide.

3. **Salinity gradient seasonally variable**, due to seasonal differences in river discharge and local precipitation. Water generally fresh throughout "wet" season (December-June), with regular seasonal incursion of slightly brackish (~1-2ppt) water into western Delta during "dry" season (August-October). Greater incursion of brackish water could occur during severe drought or extremely dry years.

Stressors: Diversions, impoundments (dams and levees), unnatural barriers, channelization of rivers, rock rip-rap and other water management actions.

B. General Geomorphic Attributes

1. **Extremely flat topography**, with few places exceeding level of wetland plain by more than ten feet.

2. **Highly channelized topography**, with network of waterways of varying dimension branching throughout

3. **Riverine channels geomorphically/hydrologically connected to wetlands**, continuously by distributary channel system, and intermittently by levees low enough to be regularly topped during flood events.

4. Natural sediment production and acquisition resulting in **net soil accretion at a rate comparable to sea level rise** rate, resulting in negligible net change in sea level. Sediment delivery from external sources occurs mainly during large flood discharges from the Sacramento River.

Stressors: diversions, impoundments (dams and levees), unnatural barriers, channelization of rivers, rock rip-rap, recreational boating, and land use changes such as conversion to agriculture and urban development.

C. NATURAL HABITATS: TYPES AND ATTRIBUTES

General Attributes (Among-habitat):

1. **Natural landscape mosaic.** Sufficient habitat diversity, distribution, proportionate areal extent, and connectivity to ensure full support of native biodiversity and essential ecosystem processes

2. **"Healthy" water/sediment quality.** Range and variability of nutrients, water column dissolved oxygen, sediment DO and redox, salinity, temperature, water clarity/light penetration, turbidity and water quality (lack of biotoxicity) sufficient to support all native species and essential ecological processes

3. Because Delta is transitional between freshwater and brackish/marine systems, it contained an **unusually high concentration of biodiversity apparent in many taxa**

Specific Attributes (Within-Habitat):

<u>Primary System Habitats (I): Tidally Influenced Area</u>

1. Intertidal Wetlands - complex, swamp-like mosaic of sub-habitats, including areas dominated by emergent vegetation, smaller tidal drainage channels, shallow lakes, ponds and pools, and mudflats

a. Minimal topographic relief

b. high overall plant diversity (over 40 native species), with tule marsh dominant in many areas

c. Substantial seasonal variability in average level of inundation

d. fresh water conditions generally prevail, but seasonal incursions of slightly brackish water not unusual

e. Sediment composition mainly organic (peat) with minor but necessary (for stabilization) inorganic contribution

2. Subtidal Waterways - includes two major types (riverine channels and distributary sloughs), each composed of three general sub-habitats: water column, benthic, and littoral zone (within-bank area alternately submerged and exposed by changing water levels)

a. Riverine channels: Net one-way, downstream water movement controlled primarily by river discharge. Comparatively high velocity, low residence time, minimal benthic vegetation, low plankton concentrations

b. Distributary Sloughs: Bidirectional water movement controlled mainly by tides. Comparatively low velocity, high residence time, well-developed benthic vegetation, higher plankton concentrations

3. Riparian/other elevated (supratidal) landforms within subtidal/intertidal areas

a. occupied by plant and animal assemblages generally typical of Central valley river riparian zones

b. frequently topped by floods, resulting in a high-disturbance, successional habitat

Primary System Habitats (II): Beyond Tidally Influenced Area

1. Riverine Channels - see description: Lowland (Alluvial) River-Floodplain Systems (Section II; above)

2. Non-tidal Wetlands - see description: Lowland (Alluvial) River-Floodplain Systems (Section II; above)

3. Riparian Zone - see description: Lowland (Alluvial) River-Floodplain Systems (Section II; above)

Associated/Interactive Habitats (Delta Uplands)

1. native (largely perennial) grasslands
2. oak woodlands
3. chaparral
4. vernal pools

5. wildflower fields
6. dune scrub

Stressors: dams and diversions, unnatural levees, unnatural barriers, dredge-fill activities, and urban/suburban and agricultural land use modifications. Water quality is affected by toxic contaminants from agriculture, urban runoff, recreational boating

D. NATIVE BIOLOGICAL COMMUNITY ATTRIBUTES (Community Structure)

(Note: Because most larger animals (many insects, fishes, birds, reptiles, amphibians, mammals) commonly used several or all major habitat-types, biological assemblages are described here for the ecosystem as a whole rather than by habitat-type as has been done for other ecosystem-types)

Natural abundance/distribution patterns of:

Major Components	**Dominant group(s)/comments**
a. plants	**Wetlands:** tule (*Scirpus acutus*), common reed (*Phragmites australis*) and cattail most common emergent plants; **Riparian zone**: species typical of Central Valley river riparian areas, including coarse bunch grasses, willows, oak, sycamore, alder, walnut and cottonwood, blackberry and rose thickets; **Major waterways:** duckweed and benthic macrophytes common in areas of low water movement; phytoplankton likely dominated by diatoms
b. invertebrates	Mosquitos abundant and ubiquitous, other insects, benthic invertebrates; zooplankton dominated by ciliate protozoans, rotifers, copepods, and cladocerans
c. fishes	mixture of native resident estuarine (e.g., Delta smelt) and freshwater forms, and anadromous species
d. birds	extremely rich waterfowl assemblage, many others
e. mammals	diverse assemblage of small and large mammals, including tule elk, grizzly bear, beaver, river otter, bobcat, raccoon, mink, skunk. Many more species around drier periphery of swamps

Stressors: Exotic species, diversions, impoundments (dams and levees), unnatural barriers, channelization of rivers, rock rip-rap, recreational activities (boating, fishing, hunting), land-use practices (agriculture, road building); and urban development.

E. COMMUNITY ENERGETICS/NUTRIENT CYCLING ATTRIBUTES

1. **Most** of ecosystem **primary production is within wetland** habitats
2. **Most decomposition occurs within tidal and non-tidal wetland** habitats
3. **Detrital chain dominates** Delta energy cycling and transfer
4. Large amounts of **detritus exported** to San Francisco Bay

Stressors: Exotic species, land-use practices (agriculture) and urban development pollution; modification of natural topography (levees, subsided marshplains)

APPENDIX 2

ERPP Indicators Work Group

The ERPP Indicators Work Group includes both agency and stakeholder representatives from U.S. Fish and Wildlife Service, U.S. Environmental Protection Agency, Department of Fish and Game, Department of Water Resources, CALFED Bay-Delta Program, Environmental Defense Fund, The Bay Institute of San Francisco, Metropolitan Water District of Southern California and Central Valley Project Water Association. The typology, conceptual models and ecological attributes described below represent work to date by the ERPP Indicators Work Group and is subject to refinement. The attributes will be used to refine the conceptual models through an iterative process within the ERPP Indicators Work Group. Concurrently, the conceptual models and attributes will undergo review by a recently formed technical work group consisting of Interagency Ecological Program (IEP), U.S. Geological Survey (USGS), and San Francisco Estuary Institute (SFEI) technical specialists. The conceptual models and attributes will also be sent to local experts for review and input.

Ecosystem Attributes and Conceptual Models

Introduction

According to Levy et al. (1996) "The fundamental requirement of a suite of ecological indicators is that all of the important ecological attributes of the system be represented. Accordingly, indicators should include both structural and functional attributes of an ecosystem." The premise is that the suite of indicators should be measurable and provide key information on structural and functional attributes of the Bay-Delta-River system across several levels of spatial and temporal scale. Examples of structural attributes include natural landscape mosaic and high diversity of amphibians and reptiles. Functional attributes include active channel migration and floodplain construction. Ecological attributes can be thought of as those key qualities or characteristics which define ecosystem integrity. These natural attributes vary together through daily, seasonal, annual and other time frames and produce a highly variable ecosystem.

Ecological attributes for the Bay-Delta-River System are organized by broad elements which include: upland river-riparian systems, lowland river-floodplain systems, Delta and Greater San Francisco Bay (Attachment 1). These elements each encompass three or more ecological zones as described in the draft ERPP. General categories of attributes were identified (hydrologic, geomorphic, habitat, biological community, and community energetics) which reflect essential aspects of ecosystem structure and function. Understanding the ecological attributes of the Bay-Delta-River system provides a basis for developing conceptual models.

The conceptual models provide as much consistency across both ecological hierarchy and geography as possible so that information can be aggregated in a variety of ways. Input by technical experts will be more easily integrated using a common format.

Typology

The ERPP Indicators Work Group has developed a typology which is a modification of the typology described by Levy et al. (1996). This modified typology is the framework upon which landscape-scale, ecosystem-scale, habitat-scale and specialized conceptual models will be developed (Figure 1). The near-shore ocean ecosystem may be added to this typology considering the potential management actions necessary to restore anadromous species. Conceptual models may subsequently be developed for this ecosystem.

Landscape-scale Conceptual Model

The Landscape-scale conceptual model globally depicts large-scale attributes of the Bay-Delta-River system and associated watershed (Figure 2). This model depicts the structural and functional attributes which generally apply across ecosystems. Indicators developed at this scale will be based on ecological attributes such as habitat, areal extent and connectivity, habitat diversity and representativeness, and hydrologic and sedimentation regime. This model will be used to integrate the ecosystem-scale models and to convey to the public the general ecological concepts and hypotheses which are the underpinnings of restoration ecology.

Ecosystem-scale Conceptual Models

Ecosystem-scale models include the Upland River-Riparian Systems (Figure 3), Lowland River-Floodplain Systems (Figure 4), and Bay-Delta Conceptual models (Figure 5). The attributes for the Greater San Francisco Bay and Delta have been incorporated into one conceptual model called the Bay-Delta Conceptual Model by CALFED staff. As the iterative review process unfolds it may be deemed necessary to have separate conceptual models for the Greater San Francisco Bay and Delta (Text describing the ecosystem-scale models in greater detail is currently being developed).

The ecosystem-scale models are based on distinctive geomorphic and hydrologic features which warrant the development of separate conceptual models. For example, upland river-riparian systems are characterized by steep confining topography with bedrock-controlled stream channels in a narrow floodplain. These systems generally occur in upper elevation watersheds above major dams in both the Sacramento and San Joaquin Valley. Hydrologically these areas are characterized by seasonal shifts in stream levels with periodic flooding. The lowland river-floodplain systems are characterized by flat, non-confining topography with a wide floodplain area which allows for active channel migration and floodplain development. These systems have seasonal shifts in stream levels with periodic flooding but also have greater hydrodynamic complexity and large groundwater basins, particularly in the Sacramento Valley.

For undammed tributaries the 300 foot contour was chosen as the dividing line between upland-river riparian and lowland-river floodplain systems. This is the approximate boundary where alluvial soils begin. Often, the location of dams and reservoirs coincides with this boundary. The difference in hydrologic attributes above and below dams warrant using this as a boundary. The uppermost extent of tidal influence was chosen as the boundary between lowland-river floodplain systems and the Delta. Finally, Chipps Island, to coordinate with the legal definition of the Delta, was selected as the boundary between the Delta and the Greater San Francisco Bay.

Indicators developed at the ecosystem-scale will include an assessment of ecological attributes such as habitat, areal extent and connectivity, habitat diversity, and hydrologic and sedimentation regime. For example, in lowland river-floodplain systems the integrity of fluvial geomorphology will be evaluated using indicators of processes such as channel meander, channel/floodplain interactions and surface/groundwater exchange.

Habitat-scale Conceptual Models

Conceptual models of habitats need to be developed to depict our current understanding of habitat structure and function. Habitat models could be used to assess technical feasibility and desirability of proposed restoration projects and to evaluate the results of restoration and management actions. A detailed riparian forest habitat model might include such attributes as hydrologic and sedimentation regime; plant composition, diversity and cover; faunal diversity; and reproduction of neotropical migrant birds. Such a model could be used to construct alternative hypotheses regarding, for example, the ecological effects of a levee setback.

Specialized Conceptual Models

Specialized conceptual models include models of individual tributaries, stream reaches, sections of rivers, biological communities, species populations and ecological processes. The Lower American River Conceptual Model (Figure 6) is an example of a tributary model that could be used to track local system health and demonstrate the contribution of a particular waterway to landscape-level ecological integrity. The lower American River is essential to the migration, spawning, rearing and outmigration of chinook salmon. Conceptual models and indicators for the lower American River will be developed with the assistance of technical specialists having expertise on this system. For example, the Department of Fish and Game's Stream Evaluation Program, the Water Forum, and Sacramento Area Flood Control Agency technical specialists will likely be contributors to this process. While the general ecological attributes of tributaries in a particular geographic area may be the same, the individual tributary indicators and stressors will likely vary to reflect the different areas of concern for each tributary.

A Bay-Delta food-web model is an example of a biological community model which may be developed. Species population models that may be developed include population models, life-history and fish loss models.

Quantitative models of hydrology, sediment transport, and carbon budget are examples of specialized conceptual models of ecological processes.

Conceptual Model Structure and Symbolic Conventions

The conceptual models depict ecological attributes, linkages, and stressors in a very general way and are a starting point from which to develop more detailed models of ecosystem processes. For example, hydrology, fluvial geomorphology, and instream habitat are represented by interconnected boxes on each of the ecosystem-scale models. Where there are lines connecting boxes there is an assumed relationship between attributes that can be quantified by a regression equation or some other statistical model.

The models, as currently developed, have an input/output structure which depict sediment supply, hydrology, water quality, nutrients, and migrating species as the key ecological attributes in the Bay-Delta-River system. Attributes and other terms included in the model diagrams are defined in Table 1.

Stressors are adverse changes to ecosystem processes, habitats, and species that are human caused and are depicted in the conceptual models by numbers on the model diagrams (Table 2). At each box and arrow in the conceptual models, natural processes and human stressors change the nature of the transmission of these ecological attributes through the system. Stressors in the model diagrams are the same ones described in Volume I of the draft ERPP (Only a few stressors are shown on the diagrams to serve as examples. Additional stressors will be identified and included in the diagrams as the conceptual models are refined by technical experts. The ERPP Indicators Work Group will continue to review, refine, and better describe stressors).

Indicator Development Process

The ERPP Indicators Work Group has now begun engaging technical experts having knowledge of particular species, habitats, and ecological processes. Technical experts will assist in the iterative process of developing conceptual models and indicators of ecological integrity for the Bay-Delta-River system.

There may be two or more sets of indicators depending on the intended purpose and audience. Because the indicators will be utilized by the public, management, and technical experts, the indicators will have varying degrees of complexity. For example, a set of indicators suited for the public may consist of just a few overarching measures of ecological health that are easily understood by the general reader whereas, a set of indicators used by the scientific community could be more esoteric and require a technical background to understand.

Once indicators are selected, a range of target values will be developed for each indicator. The targets will define levels that achieve ecological integrity or health based on our best estimate of historic states, reference conditions or other information. Indicator targets will be revisited and refined based on new information generated by the adaptive management process. Such information could include: analysis of historical conditions and processes; presence of introduced species;

incorporation of natural fluctuations; and future growth and development.

Monitoring and Adaptive Management

A comprehensive monitoring program is being developed by IEP/USGS/SFEI to assure the indicators will be measured. Evaluation of the results of the monitoring and indicators programs will require specific expertise, particularly in the early years of the restoration program. An integral portion of the evaluation should be provided by those area- and species-specific experts that helped developed the indicators. As the restoration program proceeds the linkages between attributes and the effects of stressors on the Bay-Delta-River system will become more clearly understood, providing knowledge upon which to base ecosystem management decisions. Monitoring data and the evaluation of indicators will be incorporated into the adaptive management process.

Next Steps

Pursuant to the recommendations of the Scientific Review Panel and stakeholders, CALFED is developing a draft ERPP Strategic Plan to integrate more science into the program. A three-tiered Science Program is being developed and will consist of a Drafting Team to work on the Strategic Plan, a Standing Science Body of technical experts to provide guidance on complex scientific issues, and an Independent Scientific Panel to review draft ERPP work products. The IEP/USGS/SFEI technical work group has been charged with the development of an overall monitoring program for the CALFED Bay-Delta Program and to provide technical guidance on ecological conceptual models and indicators. The IEP/USGS/SFEI technical group has been asked to review draft conceptual models and other products of the ERPP Indicators Work Group.

The iterative process of refining the conceptual models is an ongoing effort. Once the generalized conceptual models have been reviewed and are in good form the ERPP Indicators Work Group will work closely with technical experts and conduct focused workshops to develop more detailed conceptual models and ecological indicators. The CALFED Strategic Plan and Science Program, IEP/USGS/SFEI technical work group and the ERPP Indicators Work Group are concurrent programs which will have substantial, ongoing interactions as these programs are jointly developed.

REFERENCES

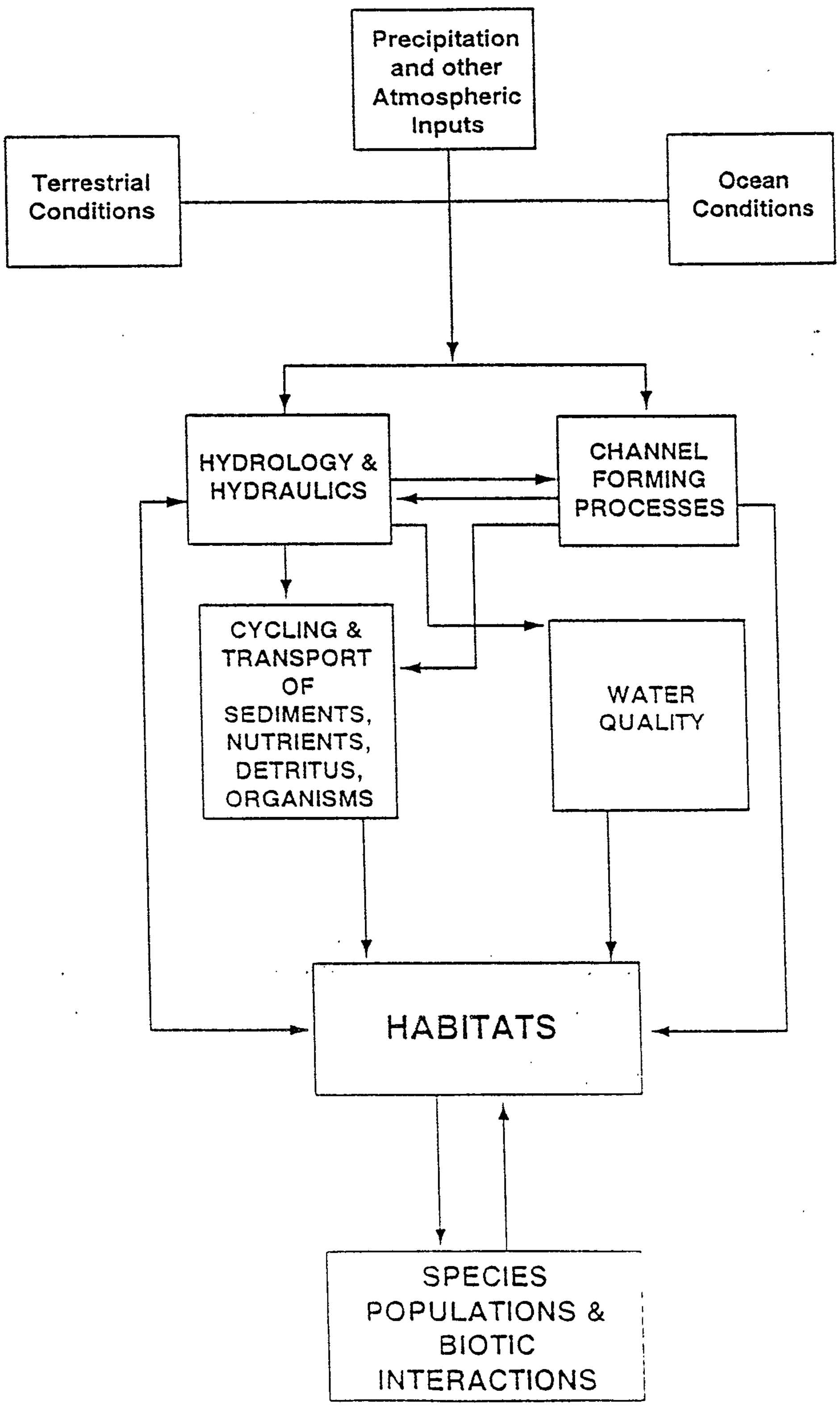
Levy, K., T. F. Young, R. M. Fujita and W. Alevizon. 1996. *Restoration of the San Francisco Bay-Delta-River System: Choosing Indicators of Ecological Integrity*. Center for Sustainable Resource Development. University of California at Berkeley.

Typology Schematic

Figure 1

Landscape-scale	Bay-Delta-River System			
Ecosystem-scale	Upland River-Riparian Systems	Lowland River-Floodplain Systems	Bay System	Delta System
Habitat-scale	Riparian Forest Habitat	Benthic/ Mudflat	Instream Habitat	Floodplain Habitat
Specialized Conceptual Models	Lower American River	Sacramento River	Sediment Supply	Salmon Population

Landscape-level Conceptual Model
Figure 2



Bay-Delta Conceptual Model

Figure 5

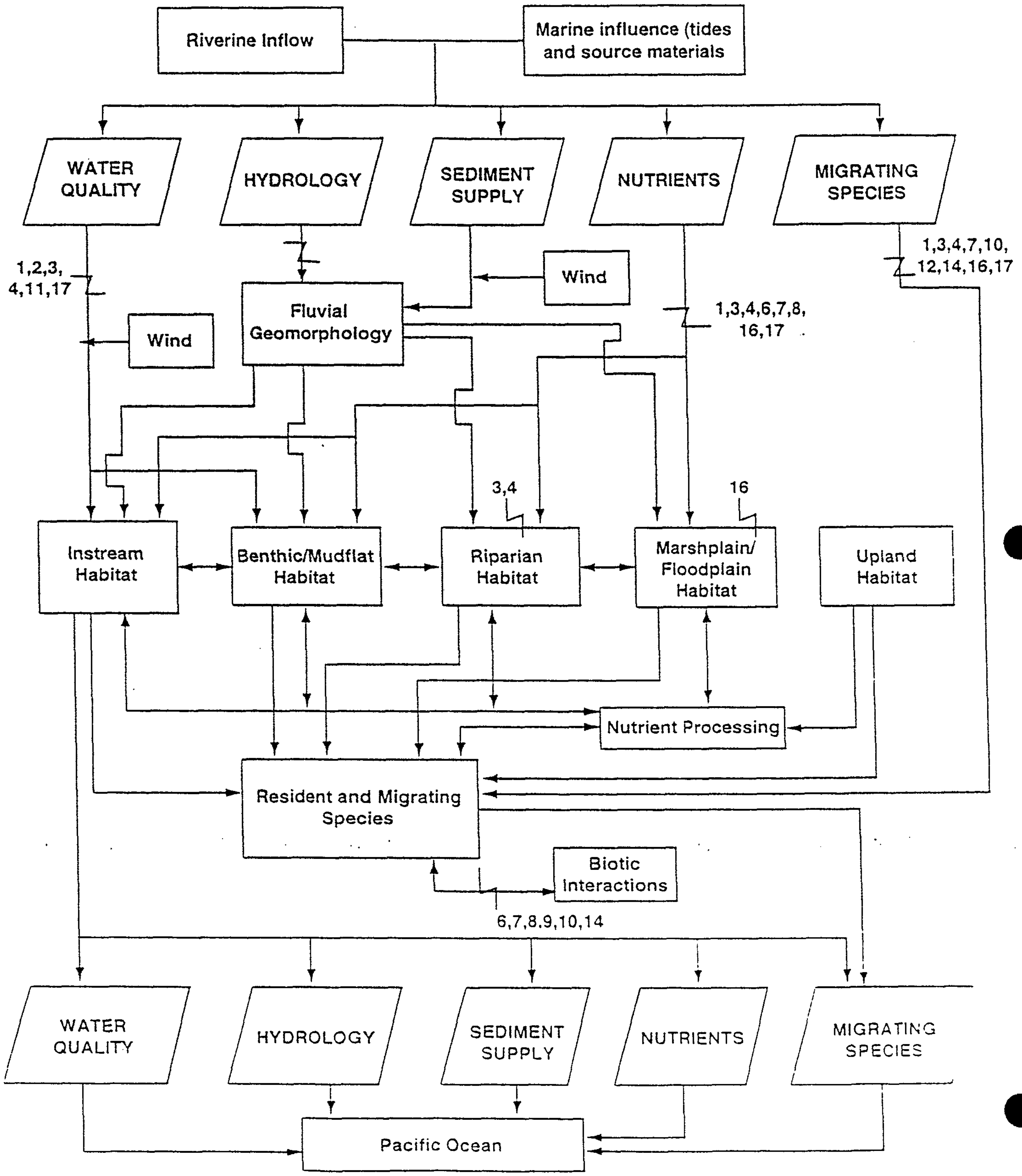


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Table 1. Definition of Terms in Model Diagrams

Hydrology

Hydraulics- The static and dynamic behavior of water.

Hydrology- Fresh water flowing in rivers and Bay-Delta channels derived from reservoir releases and surface and groundwater discharges into river channels, the Delta and Bay. Stream flow varies seasonally and annually with rainfall, run-off and water supply management. Hydrology also includes surface/groundwater interactions.

Marine influence- Tidal effects and the input of nutrients and sediments from the Pacific Ocean to the Bay-Delta estuary.

Ocean conditions- Temperature, salinity, nutrients, ocean currents and meteorological characteristics on a global scale.

Pacific Ocean- Largest and deepest ocean.

Precipitation and other atmospheric inputs - Rainfall and dryfall.

Riverine inflow- Freshwater input.

Water Quality - Those chemical and physical characteristics of water that have bearing on the surrounding biota.

Geomorphology

Channel forming processes- Fluvial geomorphological processes including accretion and erosion, sediment transport, and channel/floodplain interactions.

Fluvial geomorphology- Physical processes associated with moving water such as accretion and erosion, sediment transport, and channel/floodplain interactions.

Sediments - Mineral or organic silts, sands, gravel, cobble, and woody debris that naturally enter, deposit, erode or are transported by river or stream flow.

Terrestrial conditions- Physical geography, including topography and geological formations

Habitats

Benthic/mudflat habitat- Channel, slough and bay substrates consisting of fine grain minerals, detritus, and living organisms.

Floodplain habitat- Seasonal wetlands, fresh emergent marsh, riparian oak woodland, and grasslands.

Instream Habitat - That habitat within streams and rivers that must be totally submerged to be viable habitat for those species utilizing it.

Marshplain habitat- Tidal salt and brackish marsh.

Riparian Habitat- Scrub, woodland, and forest plant communities associated with the shorelines of rivers and the Delta.

Upland Habitat- Scrub, woodland, forested habitats; perennial or annual grasses in the drier. higher elevations of the upper watersheds.

Population and Community

Biotic interactions- Impact of species on each other; population regulation; predator/prey relationships.

Migrating species- Terrestrial and aquatic species which migrate or have dispersal movements across geographic zones.

Resident species- Terrestrial and aquatic species which do not migrate and which have limited dispersal movements.

Community Energetics and Nutrients

Detritus- Disintegrated organic and inorganic matter.

Nutrients- Organic and inorganic nourishing substances.

Nutrient processing- Biogeochemical cycling.

Other terms:

Dams and reservoirs- The physical structures on tributaries which capture runoff and allow for the storage of surface water.

Wind- A movement of air.

Table 2. Stressors Legend

1	Water Diversions
2	Dams, Reservoirs, Weirs, and Other Human-made Structures
3	Levees, Bridges, and Bank Protection
4	Dredging and Sediment Disposal
5	Gravel Mining
6	Invasive Aquatic Plants
7	Invasive Aquatic Organisms
8	Invasive Riparian and Salt Marsh Plants
9	Non-Native Wildlife
10	Predation and Competition
11	Contaminants
12	Fire
13	Fish and Wildlife Harvest
14	Artificial Fish Propagation
15	Disturbance
16	Land Use
17	Degraded Water Quality